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Title: Numerical Analysis of Heat Transfer During Surface Pasteurization of Hot Dogs with Vacuum-Steam-Vacuum Technology

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Numerical Analysis of Heat Transfer during Surface Pasteurization of Hot Dogs with Vacuum–Steam–Vacuum Technology

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ABSTRACT: The objective of this study was to validate the fundamental heat-transfer mechanism governing the process of vacuum-steam-vacuum surface pasteurization of hot dogs. It was hypothesized that the steam could not directly flow into the pores below the surface of hot dogs, and the heat was transferred into these areas by conduction. A numerical analysis program was first developed to estimate the heat-transfer coefficient between steam and hot dogs and was then used to simulate the temperature distribution at different locations below the surface. The hypothesis and computer simulation model were successfully validated using hot dogs surface-inoculated with *Listeria innocua*. Results showed that the heat from saturated steam must be conducted into the interior to kill *L. innocua* harboring in the pores and irregularities below the surface of hot dogs. Results of computer simulation and biological validation also suggested that heating must be maintained at 138 °C for at least 25 s to achieve a complete elimination (> 8 log colony-forming units per gram) of *L. innocua* from hot dogs.

Keywords: *Listeria monocytogenes*, *Listeria innocua*, hot dogs, surface pasteurization, numerical analysis

Introduction

Listeria monocytogenes is a serious foodborne pathogen associated with ready-to-eat (RTE) meat products. Confirmed cases of outbreaks of this organism have been reported in recent years involving multiple states across America (CDC 1998, 2000, 2002, 2003). Although the rate of listeriosis is usually low, the fatality rate is high among people with compromised immune systems and who are young, old, or pregnant. According to the Centers for Disease Control and Prevention (CDC), each year an estimated 1100 people in the United States experience serious illness from listeriosis, approximately 25% of whom die as a result (FSIS 1999). Because of the high fatality rate of listeriosis, both Food and Drug Administration (FDA) and Food Safety and Inspection Service (FSIS) maintained "zero-tolerance" policies in RTE products.

RTE meat products, such as hot dogs and lunchmeats, are fully cooked and are supposedly free of foodborne pathogens, including *L. monocytogenes*. However, postprocessing handling presents real risks for cross-contamination in cooked products. For example, peeling of casings after the thermal processing of hot dogs was found to be primarily responsible for the recontamination of *L. monocytogenes*, according to a study conducted by scientists from CDC and USDA (Wenger and others 1990). Largely due to poor sanitary conditions, condensates from food-processing machineries, contaminated with *L. monocytogenes*, may potentially drip or spread onto processed food surfaces before final packaging. As a result, RTE foods contaminated with *L. monocytogenes* may enter the market, potentially causing outbreaks of listeriosis. In 2003, USDA-FSIS issued an interim final rule that requires federal establishments producing certain RTE meat and poultry products to adopt meaningful steps to further reduce the incidence of *L. monocytogenes*.

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Vacuum-steam-vacuum, or VSV, is a rapid pasteurization technology developed in recent years to kill foodborne pathogens on contaminated surfaces of solid foods. This technology was originally conceptualized by Morgan (1994) and has been tested in both small and pilot-scale VSV systems. It uses vacuum, steam, and vacuum in sequence to expose food surfaces to ultrahigh temperature steam or gas in an extremely short period of time, thus killing bacteria attached to food surfaces as well as in the subsurface structures. Morgan (1994) hypothesized that bacteria may hide in small pores and irregularities near the surface of solid foods. Because of the presence of moisture vapor and incondensable air in the vicinity of small pores and irregularities (that is, subsurface structures), there exists a layer of insulation blanket, preventing steam from directly reaching the bacteria hiding in these small areas. Thus Morgan (1994) proposed using an initial vacuum treatment to remove the air and moisture vapor from small pores and irregularities under the surface, thereby exposing the bacteria to the subsequent steam treatment. Because of the removal of the insulation layer in the initial vacuum treatment, ultrahigh-temperature saturated steam can freely and quickly flow into the small micron-sized pores, directly contacting the bacteria in these areas and thus instantaneously killing the microorganisms. After the steam treatment, the immense heat is removed by a second vacuum process. Each operation in a VSV process operates in milliseconds, allowing rapid pasteurization of food surfaces without inducing physical and chemical damage to the products. The VSV process may be repeated several times in an operation to achieve the goal of pasteurization.

Several studies have been reported regarding the effectiveness of VSV for inactivating bacteria on contaminated surfaces of various solid foods. Morgan and others (1996a) conducted a study using a small-scale VSV device to treat small pieces of chicken breast meats (~5 g). About 10^7 cells of a nonpathogenic bacterium, *Listeria innocua*, were applied to chicken meat pieces. Under steam temperatures of 127 °C, 138 °C, 149 °C, or 157 °C for 26 ms, the bacterial kill was 2.2, 4.0, 2.8, and 2.7 logs, respectively. Under 121 °C steam for

48 ms, 4.0, 2.8, 2.4, 2.5, and 1.9 log-reductions were observed in fresh chicken meat, thawed frozen chicken meat, thawed frozen chicken skin, fresh lean beef, and fresh lean pork, respectively. Similar observations were reported by Morgan and others (1996b) in another VSV study. Small pieces (about 5 g) of chicken meat strips inoculated with 10^7 freshly grown *L. innocua* were treated at temperatures ranging from 126 °C to 139 °C with multiple cycles (10 to 40) of steam treatment (52 to 124 ms). After multiple cycles of VSV treatments with a total steam time up to 4.12 s, the effective bacterial reduction was between 2.7 - 3.8 logs. The authors acknowledged the high number of bacterial survival but attributed it to the protective effect of meat to bacteria. The authors did not investigate the effectiveness of heat transfer from steam to meat samples.

Studies were also conducted in larger pilot-scale VSV units. Kozempel and others (2000a) reported a study using a pilot-scale VSV system to treat commercially available chickens (whole, half, and drumsticks). Under the steam treatment conditions of 116 °C, 121 °C, or 157°C for 1 s, no meaningful reduction (0.3 log max) in *Escherichia coli*, coliforms, and aerobic plates counts (APC) was observed in the cavities of chickens after treatment. No reduction in the counts of *E. coli* was observed on the surface of whole chickens. With original counts between 2 to 5.6 logs, a range of 0.2 to 1.2 log reductions in coliforms and APC was observed on the surface of whole chickens after VSV treatment. For drumsticks treated at steam temperatures ranging from 116 °C to 138 °C for 0.1 s, the reduction in APC was between 0.1 and 1.2 logs. Kozempel and others (2001a) conducted another study to pasteurize chicken carcasses using a pilot-scale VSV unit improved with specially designed mandrels capable of directly injecting steam into the cavities of chickens. Applying 138 °C or 143°C steam for 0.1 s to chickens surface-inoculated with *L. innocua* with an initial bacterial count about 4 - 5 log (colony-forming units [CFU]/mL), Kozempel and others (2001a) observed that the decrease in bacterial counts was between 0.7 and 0.8 log CFU/mL. In another study to treat catfish surface-inoculated with *L. innocua* at an average level of 5.2 log CFU/mL, Kozempel and others (2001b) reported that the reduction in bacteria counts was about 2 log CFU/mL after applying multiple cycles of steam treatment at 143 °C. Sommers and others (2002) conducted a study to investigate the combined effect of bacterial kill in ham using VSV and ionizing radiation. Ham meat or skin was inoculated with about 8 log/per sample of *L. innocua*. Under the conditions of 137 °C steam temperature at 0.1 s per cycle for 2 cycles, the VSV process contributed to an average reduction of 1.69 logs on ham meat or 2.35 logs on ham skin.

The VSV process was more effective for treating solid foods with smoother surfaces. Kozempel and others (2000b) reported that approximately 4.18 to 5.54 logs of reduction in *L. innocua* counts were observed using VSV to treat hot dogs under various conditions (138 °C, 0.3- to 0.4-s steam time per cycle, 2 to 4 cycles). However, a significant amount (0.65 to 2.00 log CFU/mL) of *L. innocua* survived the VSV processes. Because hot dogs are considered RTE products, no *Listeria* is allowed in the final products. Apparently the VSV process could not completely kill *L. innocua* on hot dog surface. Because *L. innocua* is often used as an indicator organism and because *L. monocytogenes* is generally considered among the most heat-resistant strains of non–spore-forming microorganisms (Mackey and Bratchell 1989; Foegeding and Stanley 1991), the current VSV technology is unlikely capable of rendering hot dogs free of *L. monocytogenes* after the treatment. Similar observations were found in other studies reported by Kozempel and others (2002) using VSV to treat a variety of fruits and vegetables surface-inoculated with 4.1 to 6.4 log CFU/mL of *L. innocua*. Although 3.1 to 4.7 logs of bacterial kill were achieved, 1.0 to 1.6 log CFU/mL of *L. innocua* was observed to have survived the intense heating, regardless of the steam temperature (138 °C or 143 °C), heating time (0.1 or 0.2) in each cycle, and the number (1 to 3) of cycles in a treatment process. If these treated fruits and vegetables containing *L. monocytogenes* were used to make unpasteurized juices, salads, or other RTE foods, potentially they may cause listeriosis if consumed by the at-risk population.

The steam temperatures used during VSV processes are very high (116 °C to 157 °C). Although the heating time in each cycle is very short, the total heating time after multiple cycles is in the range of seconds, sufficiently long to eliminate all non–spore-forming pathogens on food surfaces. One interesting observation in the published literature is that the bacterial kill was neither proportional to the increase in the steam temperature nor to the heating time. The reduction in bacterial counts remained almost the same, regardless of the steam temperature or the total heating time. This intriguing experimental observation is in direct contradiction to known thermal inaction kinetics. For most microorganisms under isothermal conditions, increasing heating time should lead to an exponential decrease in bacterial counts, as specified by the D-values. The increase in heating temperature should cause the D-values to decrease exponentially also, as described by the z-values. According to the kinetics of thermal inactivation, it is possible to completely eliminate bacteria when the temperature is high enough and the heating time is long enough. With known kinetics, it is also possible to estimate the extent of bacterial destruction according to the time-temperature history of a thermal process. All experimental results reported in the published literature pointed to the fact that VSV processes substantially deviated from the standard thermal inactivation kinetics.

The basic hypothesis of this study is that the gaseous steam cannot freely flow into the small micro-sized pores, cracks, and other irregularities beneath the surface of hot dogs under the conditions of VSV. Therefore, the immense latent heat from the saturated steam cannot be delivered directly to the bacteria hiding in these areas. Instead, heat is transferred from the steam to the surface of hot dogs by convection and continues to penetrate into the interior by conduction. Because the meat emulsion forms networks of protein gel after cooking, it is unlikely that pathogens could penetrate deep inside the interior of hot dogs. However, the removal of casing after cooking may form a shallow incision on the surface of hot dogs. If cross-contamination occurs during the subsequent operations transferring the products to the final packaging machine, it is in the shallow incisions where bacteria may hide and aggregate. To ensure a complete destruction of *L. monocytogenes* hiding under the surfaces of RTE products such hot dogs after cooking, it is necessary to increase the temperature in the deepest pores that may potentially harbor this organism to a lethal point. If the products are then aseptically packaged, they will be free of *L. monocytogenes*.

Therefore, the objective of this research was to use computer simulation to analyze the heat-transfer process during a typical VSV treatment. The aim was to understand the temperature distribution during VSV processes and determine the minimum requirements for establishing thermal processes to eliminate *L. monocytogenes* on the surfaces of RTE products such as hot dogs.

Materials and Methods

Hot dogs

Frozen beef hot dogs were purchased from a local manufacturer. Each hot dog was had a 2.2-cm dia and 13.3-cm length. The hot dogs were manufactured in the same batch without adding any antimicrobial agents and were available in 1-lb (0.454 kg) vacuum

packages. After hot dogs were received, they were kept frozen at –30 °C overnight and then irradiated to sterility using Cs^{37} γ-ray (Thayer and others 1995). Samples were kept frozen at about –20 °C in a freezer until used in experiments. Before VSV treatment, frozen hot dogs were thawed overnight in a refrigerator (at about 4 °C).

VSV device

Figure 1 illustrates the VSV device used in this study. The VSV chamber was made from a stainless-steel pipe, with a 4.13-cm internal dia, 4.45-cm external dia, and 30.48-cm length. One end of the chamber was connected to a 3-way valve. Depending on the position of the 3-way valve, the chamber could be either open to steam, vacuum, or atmosphere. The 3-way valve was driven by a servo motor with its position precisely monitored by an optical disk encoder.

The other end of the chamber was used for sample loading. A stainless-steel probe, modified from a standard thermocouple probe, was used to hold a sample in the VSV chamber. The probe had a 0.3175-cm dia and 18-cm length, with one end fixed to the cap of the VSV chamber. Only 1 hot dog could be loaded into the VSV chamber at each time.

A pressure sensor was connected to a port in the middle of the VSV chamber. To prevent any loss of the steam energy, the VSV chamber was covered with a layer (about 3.8 cm) of insulation foam. Between the insulation layer and the chamber, electric belt heaters were wrapped around the chamber. Except for loading and unloading samples, the VSV apparatus was operated by a computer-based control system.

VSV operation

A thawed hot dog was attached to the sample holder by inserting the holder probe along its centerline, approximately ¾ into the sample. After the sample was loaded to the chamber, the sample port was manually closed. The 3-way valve was actuated to complete a sequence of VSV operations. Driven by a computer and a controller, the valve was first switched to the vacuum position to evacuate air from the VSV chamber, then to the steam position to flush steam into the chamber, and then back to the vacuum position to remove the steam, and finally back to the original position. Next, the hot dog sample was unloaded from the VSV chamber. The residence time at each position was independently controlled and adjusted. Three steam temperatures, 110 °C, 123.9 °C, and 137.8 °C, corresponding to 230 °F, 255 °F, and 280 °F, were used to treat the surface of hot dogs. The operating time for each operation in a cycle, including initial vacuum, steam, and final vacuum, was set at 2 s. During each operation, the hot dog surface temperature and the chamber pressure were simultaneously monitored and recorded at a 5-ms interval using the methods described in the following sections.

Temperature and pressure sensors

The VSV processes reported in the literature were operated at very high speeds. The vacuum and steam exposure time was between 50 to 1000 ms in a cycle. Most temperature sensors available in the market could not respond fast enough for the VSV process. To measure the surface temperature of hot dogs, ultra-fine (52 AWG) thermocouple wires (Type-T) were custom-ordered from California Fine Wire Co. (Grover Beach, Calif., U.S.A.). Each strand of the thermocouple wires was 1.98×10^{-3} cm (0.00078 in, or 52 AWG) in diameter and was coated with a thin layer of heavy polyurethane/nylon for electric insulation. Each pair of thermocouples was welded in a thermocouple welder (Model 116SRL, B. J. Wolfe Enterprises, Inc., Agoura Hills, Calif., U.S.A.), which was capable of welding metal wires with sizes ranging from 55 to 20 AWG. Each pair of thermocouples was tested for electrical conductivity and total resistance and was calibrated before being used to measure surface temperatures during VSV processes. The response times of the thermocouples were less than 1 ms.

To measure the pressure response in the treatment chamber during a VSV process, a pressure sensor (Model AF-Al-G-V2-N1, DJ Instruments, Billerica, Mass., U.S.A.) was used. This pressure sensor was capable of measuring pressures ranging from vacuum to 5.0 bar (gauge). The response time of the pressure sensor was less than 1 ms according to the manufacturer. The pressure sensor was factory-calibrated and ready for use when delivered.

Instrumentation

To measure temperature, a 12-bit high-speed thermocouple data acquisition board (ADAC 5508TC, American Data Acquisition Corp., Woburn, Mass., U.S.A.) was used. This board had 8 A/D chan-

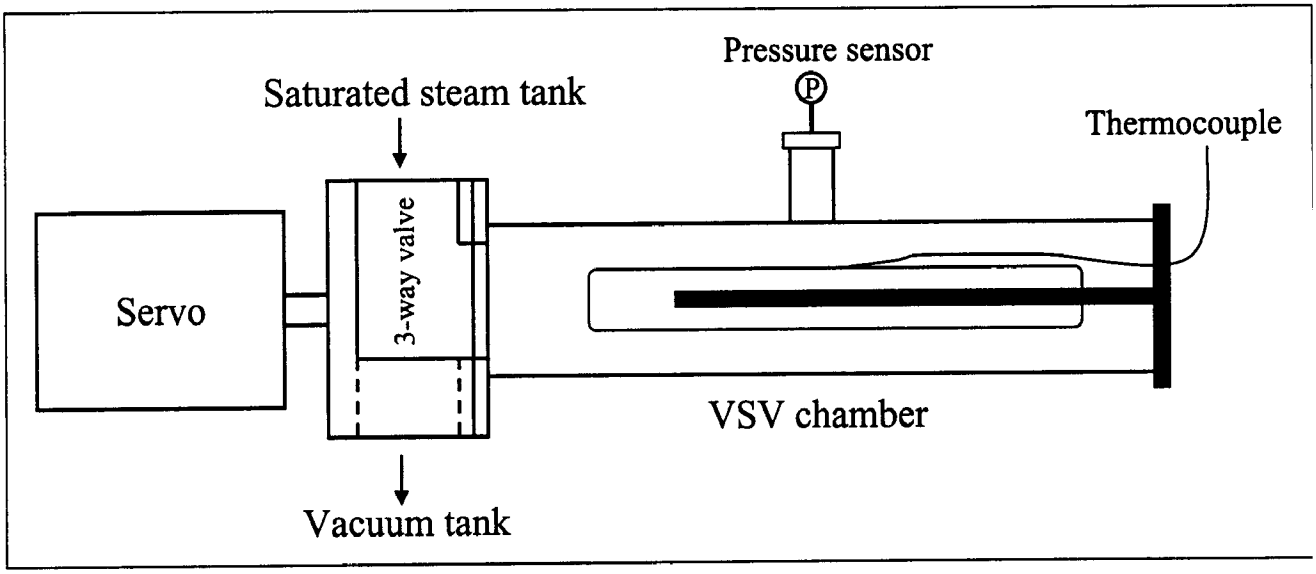

Figure 1—The vacuum-steam-vacuum apparatus used in this study

nels and could be directly inserted into an ISA bus of a personal computer. The total hardware conversion time was 85 μs. The maximum acquisition rate was 8 kHz.

To measure the signals from the pressure sensor, another high-speed A/D converter (PCI-DAS1200, Measurement Computing Corp., Middleboro, Mass., U.S.A.) was used. This was a 12-bit, 8-channel PCI board, with a minimum data throughput of 300 kHz.

Measurement of sample surface temperature and chamber pressure

To monitor and measure the surface temperature of a hot dog sample during a VSV treatment, a thermocouple was carefully attached onto the hot dog surface after it was mounted to the sample holder (Figure 1). The attachment of the thermocouple was accomplished by first applying a tiny drop of super glue (cyanoacrylate) on the surface of the hot dog sample, followed by lightly pressing the thermocouple tip against the super glue. The super glue was then carefully spread around the tip area of the thermocouple until it dried. After that, the hot dog sample with the thermocouple was loaded into the VSV chamber. After the completion of a VSV process, the thermocouple was separated from the hot dog by soaking in acetone for 15 to 30 min to dissolve the super glue.

The thermocouple attached to the sample surface was connected to the ADAC 5008TC data acquisition board. The voltage signals from the pressure sensor were wired to the PCI-DAS1200 A/D board. A data acquisition software LabTech Notebook (Version 10, Andover, Mass., U.S.A.) was used to simultaneously collect the temperature and pressure signals at a sampling rate of 200 Hz.

Heat conduction

The VSV process was a typical unsteady-state 1-dimensional heat-conduction problem with a convective boundary condition. As high-pressure saturated steam fluxed into the treatment chamber previously vacuumed, it immediately expanded to fill the entire chamber. Because the chamber was relatively small, a small amount of steam instantaneously condensed, releasing its intense thermal energy to heat the residual air in the chamber. Equilibrium was rapidly established between the treatment chamber and the saturated steam. As a result, the chamber temperature should rise almost immediately to the steam temperature.

In the meantime, heat transfer occurred on the surface of hot dogs. As steam condensed, its latent heat was released from the steam onto the hot dog surface. The surface temperature began to rise as a result. Heat continued to diffuse into the interior of hot dogs along the radial direction. For hot dogs with a cylindrical geometry (Incropera and DeWitt 1996), the 1-D unsteady-state heat conduction during a VSV process was governed by

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right). \quad (1)$$

The Robbins boundary conditions for Eq. 1 were:
At r = 0, the geometric center along the radial direction,

$$\frac{\partial T}{\partial r} = 0. \quad (2)$$

At r = R, the surface of hot dogs,

$$\frac{\partial T}{\partial r} = -\frac{h}{k}(T - T_s). \quad (3)$$

In Eq. 1 to 3, T is the temperature at any given time and location of a hot dog (°C); T_s is the steam temperature (°C); t is the heating time after steam is injected into the treatment chamber (s); r is the radius (m); α is the thermal diffusivity of hot dogs (m^2/s); h is the overall heat transfer coefficient ($W/m^2°C$); and k is the thermal conductivity of the hot dog (W/m°C). For the initial conditions of Eq. 1, it was assumed that the temperature was uniform throughout the hot dog sample.

Numerical analysis of heat conduction

The 1-D unsteady-state heat conduction equation was solved using an explicit scheme of the finite difference method (Chandra and Singh 1995). To guarantee convergence during numerical analysis, the time step (Δt) was carefully chosen such that

$$\Delta t \le \frac{\Delta r^2}{2\alpha}. \quad (4)$$

Physical properties of hot dogs

Apparent thermal conductivity and thermal diffusivity of hot dogs used in this study were experimentally measured using a line-source probe (Fontana and others 1999). The probe was constructed according to the recommendation by Murakami and others (1994) using a 22-gauge stainless-steel hypodermic needle. The length of the needle was 5.08 cm. The line heater was constructed using a 30-gauge constantan wire. A 40-gauge Type-T thermocouple was used as a temperature sensor. Both line-heater and thermocouple were put into the hypodermic needle. The void space in the needle was filled with super glue or liquid cyanoacrylate, which was stable at the temperatures of measurement. The probe construction was allowed to cure before being used in experiments. During experiments, a constant D.C. voltage source (5 V) was applied to the line heater.

Hot dogs, vacuum-sealed in plastic bags, were first submerged in a circulating water bath, maintained at 5 °C, 20 °C, 40 °C, and 60 °C, respectively, for at least 30 min to allow establishment of temperature equilibrium. The probe was carefully inserted into a hot dog along its axial center. Additional 5 min was provided to allow the probe to equilibrate with the temperature of the sample. After that, the constant D.C. power was supplied to the probe. The temperature response in the probe was measured by the thermocouple and recorded at a 5-s interval using the instrumentation system mentioned previously.

Under a constant voltage power supply, the temperature response of the probe is a function of heating time:

$$T - T_0 \cong \frac{q}{4\pi k}\left[\ln(t) - \gamma - \ln\left(\frac{r^2}{4\alpha}\right)\right]. \quad (5)$$

In Eq. 5, T is the temperature response of the probe (°C); T_0 is the initial temperature of the sample (°C); q is the power supplied to the line heater (W); k is the thermal conductivity of the sample; α is the thermal diffusivity of the sample (m^2/s); t is the heating time; γ is Euler's constant (0.5772); r is the distance between the heater and the probe. The characteristic parameters of the probe, that is, q and r, were calibrated with deionized water.

Plotting $T-T_0$ against ln(t), a linear curve should be observed with a sufficiently long heating time. Assuming the slope of the curve is K, the thermal conductivity of hot dog samples can be determined from

$$k \cong \frac{q}{4\pi K}. \quad (6)$$

The thermal diffusivity of the sample also can be determined from Eq. 5:

$$\ln(t_0) = \gamma + \ln\left(\frac{r^2}{4\alpha}\right), \quad (7)$$

where $\ln(t_0)$ is the horizontal intercept of Eq. 5.

Determination of heat-transfer coefficient h

The numerical analysis method developed previously was used to determine the apparent heat-transfer coefficient during a VSV process. The numerical iteration would start with a small initial "arbitrary" value of h. In each iteration cycle, a surface-temperature curve would be generated. The computer-generated curve was compared with each experimentally measured temperature history using the least-squares method. A least-squares error was computed. The numerical iteration continued with a small increment in the value of h until a minimum least-squares error was found. Then the final h value was used as the heat transfer coefficient of the matching VSV process. During the determination of the heat-transfer coefficient, the electric heaters were not turned on to prevent the radiation effect, which could cause the surface temperature of hot dogs samples to increase during sample loading. Only the surface-temperature history was used for determining the heat-transfer coefficients in this study. It would be preferable to use time-temperature histories at other locations below the surface of hot dogs. However, because the heating was very brief and the thermocouples used in this study were very fragile, it was not possible to accurately insert the temperature sensor into the sample to reliably measure the temperature history at any locations other than the surface of hot dogs.

Biological validation

L. innocua (SA3-VT) culture (200 mL) was grown in brain heart infusion broth (BHI, Difco/BD, Sparks, Md., U.S.A.) at 37 °C for 24 h. The concentration of bacteria in the broth was > 9 log (CFU/mL) after incubation. The culture was harvested in a refrigerated centrifuge (4 °C, 2400 × *g* for 15 min), washed twice, and resuspended in 200 mL of sterile deionized water. The bacterial suspension was immediately placed on ice.

Thawed hot dog samples were surface-inoculated with *L. innocua* by quickly dipping them in the bacterial suspension prepared previously. The dipping of hot dog samples emulated the worst-case scenario of postprocessing contamination—a pool of contaminated water may accidentally drip onto the surface of processed meats. The dipping not only uniformly coated the surface but also allowed microorganisms to enter into the small pores under hot dogs, which was essential for testing the validity of the VSV technology. Inoculated samples were placed in a sterile plastic bag and were maintained on ice before being subjected to VSV treatment (< 30 min). The overall temperature of samples was approximately 5 °C before VSV treatment.

Before biological validation studies, the VSV treatment chamber was sterilized twice using 137.8 °C saturated steam for 15 min. After the sterilization, the electric heaters around the treatment chamber were turned on and maintained at 100 °C to prevent contamination of the chamber walls.

The surface-inoculated hot dogs were placed into a sterile plastic bag and were used within 1 h after inoculation. A sample holder, made from a thin stainless-steel wire, was used to support the hot dog sample during VSV. The holder maintained a clearance between the sample and the wall of the treatment chamber. The sample holder was first soaked in 75% ethanol solution for 5 min before being used in each experiment. The inoculated hot dog was placed onto the sample holder and loaded into the treatment chamber. Each hot dog was subjected to a VSV treatment under 137.8 °C steam temperature. The initial and final vacuum time was 1 s and 2 s, respectively. The heating time during the steam treatment was 5 s, 10 s, 15 s, 20 s, and 25 s, respectively. Three hot dogs were used for each steam treatment.

After each VSV treatment, the hot dog sample was aseptically removed from the VSV chamber, then weighed and immediately submerged into 100 mL of refrigerated 0.1% sterile peptone water contained in a filter bag (SFB-0410, Spiral Biotech., Bethesda, Md., U.S.A.). Each hot dog was homogenized in the filter bag using a stomacher (Seward Laboratory Stomacher 400, London, U.K.) for 1 min. A small volume (100 μL) was extracted from the liquid portion of the homogenate, serially diluted, and then spread-plated onto the surfaces of tryptic soy agar (TSA, Difco/BD, Sparks, Md., U.S.A.). Three plates were used for each hot dog per dilution. The TSA agar plates were incubated in an incubator held at 37 ± 1 °C for 24 h. The number of bacterial colonies in each plate was manually counted and converted to CFU per gram of hot dog sample. The average count of the 3 hot dogs used in each steam treatment was used to represent the final survival counts after the VSV treatment. The biological validation was run in duplicate.

Results and Discussion

Time-temperature/pressure history

A cycle of a VSV process consisted of 3 operations in sequence. The first operation was vacuuming to evacuate the air from the treatment chamber. This operation created a negative pressure in the chamber. The negative-pressure environment allowed the high-pressure saturated steam to rapidly flux into the chamber. Also, because of the negative initial pressure, the steam immediately expanded and therefore was uniformly distributed throughout the void space of the chamber. After heating was completed, a 2nd vacuum was applied. At this point, the chamber was maintained at a very high pressure, and the exit port was maintained at a negative pressure. As soon as the exit port was open, the steam would immediately rush thorough the port, causing the pressure in the treatment chamber to drop rapidly. Figure 2 shows the temperature histories of hot dogs and pressure histories in the chamber during VSV processes. Overall, the hot dog surface-temperature history and the chamber pressure history followed the events of VSV very closely.

Apparently there was a small leakage in the 3-way valve, allowing a small amount of steam or vacuum to leak into the treatment chamber. During the 1st vacuum operation, a small amount of steam leaked into the treatment chamber, causing the surface temperature of hot dogs to creep up by approximately 10 °C to 20 °C. After the saturated steam flushed into the chamber, a small vacuum leak occurred. However, its effect on the final steam pressure in the treatment chamber was negligible. The average pressure after 1 s of steam treatment was approximately 4.4%, 2.7%, and 1.8% below the saturated steam pressures at temperatures of 110 °C, 123.9 °C and 137.8 °C, respectively.

As the steam was in contact with the cold surface of the hot dog sample, heat exchange occurred on the surface, releasing its latent heat. As the steam released its latent heat, condensation occurred. The steam condensate formed a thin layer that covered the surface of the hot dog sample. Without an external force to remove the condensate layer on the hot dog surface, the condensate would be

come an insulation blanket, preventing the hot dog surface from being directly exposed to the high-temperature steam. In the meantime, the thermal energy continued to travel into the interior of the hot dog sample. As a result, the surface temperature would not immediately increase to the steam temperature, but showed an exponential trend (Figure 2).

Because the amount of steam leaking into the chamber during the 1st vacuum operation was small and the initial vacuum time was short (2 s), it can be assumed that the leakage did not affect the overall heat transfer between the steam and the hot dog during the subsequent steam treatment. Similarly, it also can be assumed that the heat transfer between the steam and the hot dog was not affected by the small leak of vacuum during the steam operation. Therefore, in the following analysis it was assumed that the temperature creep in the 1st vacuum operation and the pressure loss in the steam operation could be ignored. Then the temperature of the hot dog when the steam operation started was equal to the initial temperature, and the chamber temperature was equal to the saturated steam temperature.

Thermal properties and determination of h

The average thermal conductivity (γ) and thermal diffusivity (α) of hot dogs measured in this study was 0.305 ± 0.013 W/m°C and $5.41 \times 10^{-8} \pm 0.74 \times 10^{-8}$ m²/s (mean ± standard error). With the thermal conductivity and diffusivity determined, the temperature history on the hot dog surface can be used to estimate the heat-transfer coefficient between the steam and hot dog sample being treated in the VSV chamber. The average heat-transfer coefficient between the steam and hot dogs was $1.71 \times 10^4 \pm 1.9 \times 10^3$ W/m²°C (mean ± standard error). Figure 3 shows the comparison between the surface-temperature histories measured experimentally and generated by numerical analysis using the average heat-transfer coefficient h (1.71×10^4 W/m²°C).

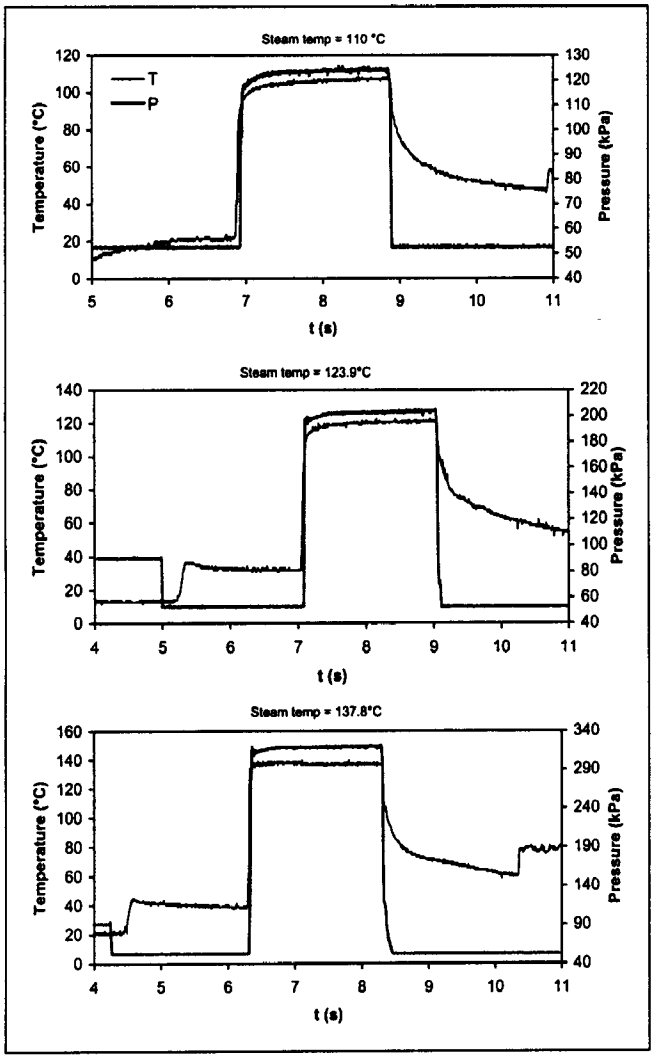

Figure 2—Representative surface-temperature histories of hot dogs and the corresponding pressure change in the treatment chamber

Computer simulation of temperature distribution

Upon the determination of the surface heat-transfer coefficient and the thermal properties of hot dogs used in the study, the temperature distribution of hot dogs during VSV treatments can be simulated by numerical analysis. Figure 4 shows the calculated distribution of temperature at various locations up to 2 mm below the surface of hot dogs subjected to 110 °C, 123.9 °C, and 137.8 °C of steam treatment. Apparently, all the temperatures below the surface of hot dogs during VSV treatments did not increase instantaneously as the steam fluxed into the treatment chamber. Although the surface temperature could rapidly reach a point lethal to the non–spore-forming microorganisms such as *L. monocytogenes*, or *L. innocua*, it would take much longer for the interior temperature to increase to a lethal temperature. Figure 5 illustrates the minimum heating time required for the temperature at 1.0 mm below the hot dog surface to reach 70 °C, 75 °C, and 80 °C in a single steam-treatment process.

Microbiological validation of the computer simulation model

Figure 6 shows the results of microbiological validation. For the 2 validation runs, the hot dogs were initially inoculated with a high concentration (about 10^{8-9} CFU/g) of *L. innocua*. Because the hot dog surface was not perfectly smooth, the number and depth of cavities/small pores might be different among hot dogs. Some hot dogs might have deeper/smaller pores than others. The difference in the distribution, structure, and depth of pores below the surface would directly affect the distribution of bacteria in hot dogs after inoculation. This difference would in turn affect the effectiveness of steam used to kill the bacteria during VSV treatments. As clearly seen in Figure 6, a 4 ~ 5 log-reduction was achieved during the first 10 s of VSV steam treatment. According to the computer simulation (Figure 4), the surface temperature reached 120 °C after 0.1 s of exposure to 137.8 °C steam. After 1 s, the hot dog surface temperature was higher than 132 °C. If the hot dog surface was perfectly smooth and all the bacteria were distributed on it, the heat from the steam would have been sufficient to kill all the bacteria after the first 10 s of steam treatment during a VSV process. However, it is obvious that although a large number of bacteria were heat-inactivated, a significant amount of bacteria still remained in the hot dogs. These bacteria could exist only at locations not directly exposed to the steam. The most possible locations were the small pores and cavities under the surface layer of hot dogs. These pores and cavities might have been filled with water with bacteria suspending in them. The bacteria under the surface were insulated from steam and were therefore unharmed after the first 10 s of exposure to 137.8 °C of steam. To inactivate the remaining bacteria under the surface, heat must be transferred to the pores and cavities. Just as in all other thermal processes, the objective of VSV must be inactivating the cells of *L. monocytogenes* hiding in the deepest pores under the surface of hot dogs. This process may take

much longer than a few milliseconds and is highly dependent on the structure and depth of the pores. In the 2 independent runs of biological validation, no viable cells of *L. innocua* were directly recovered from all hot dogs under the experimental conditions, after 20 s and 25 s of direct, uninterrupted steam exposure. According to the computer simulation (Figure 4), the temperature at 1 mm below the hot dog surface was higher than 73.5 °C after 20 s of direct steam exposure at 137.8 °C. At 25 s, the temperature at 1 mm below

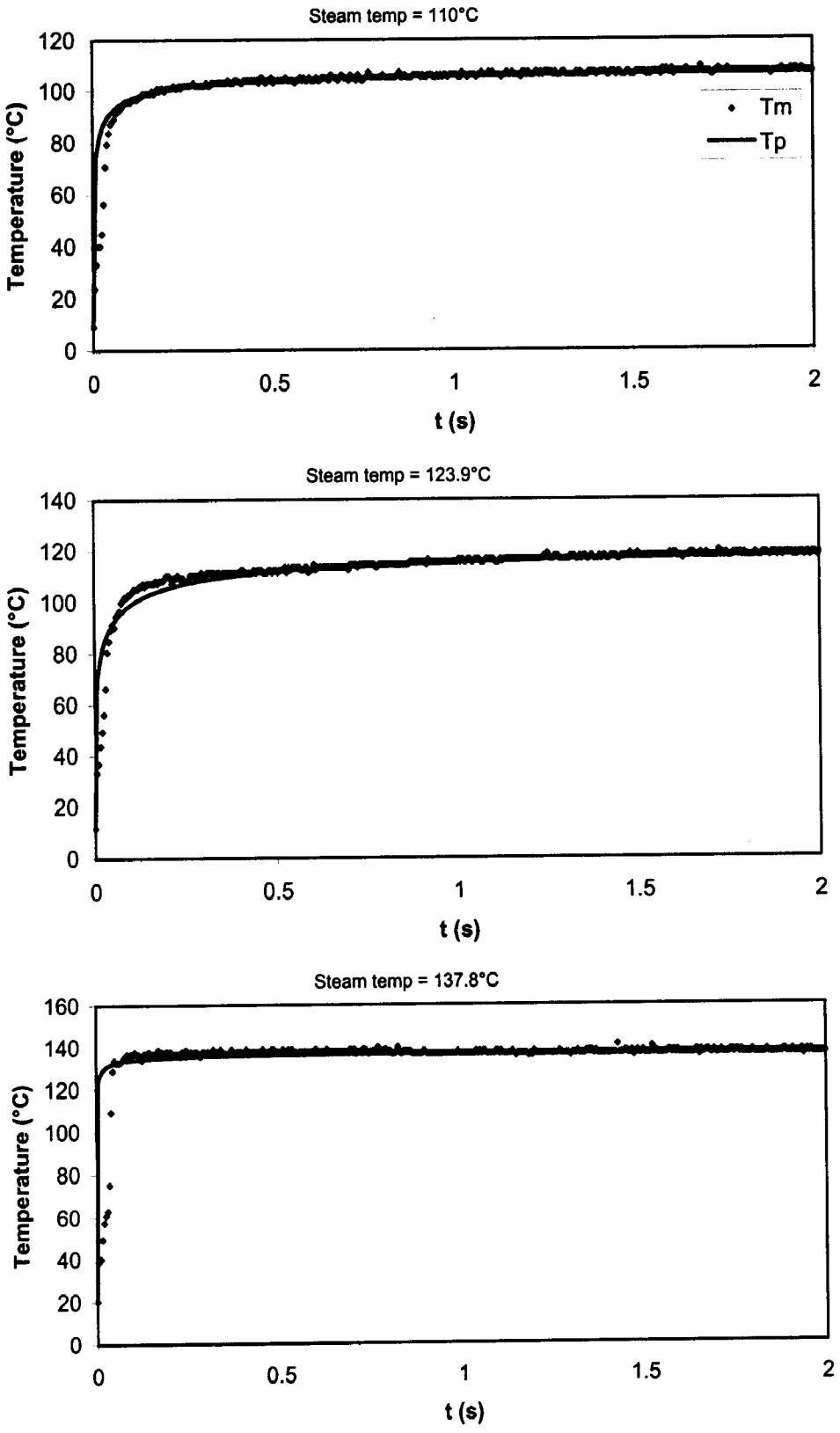

Figure 3—Measured and predicted temperatures on the surface of hot dogs subjected to steam treatment. T_m = the real-time surface temperature measured during experiment; T_p = the surface temperature predicted by numerical analysis

the surface was higher than 80 °C. Vegetative cells of pathogens are generally very sensitive to heat at temperatures higher than 70 °C. According to another study conducted by the author (Huang 2004), the D-values of *L. monocytogenes* in water at temperatures higher than 80 °C were in the ranges of milliseconds. The D-value of *L. monocytogenes* in cured meat, calculated from the data reported by Farber (1989), was about 7 ms. It is very difficult for *L. monocytogenes* to survive if the temperature was higher than 80 °C. Under normal handling conditions, it is possible to completely eliminate this organism in RTE meats when the cooking temperature is higher than 80 °C. Therefore, the preliminary results of microbiological validation agreed very well with the results of computer simulation, that is, hot dogs must be held for at least 25 s at 137.8 °C to inactivate all *L. monocytogenes* contaminated onto the surface of hot dogs during VSV treatment.

It is possible to explain why bacteria survive the severe heating conditions of VSV reported in the literature. If the bacteria were surface-inoculated onto foods, all of those superficially coated on the surface would have been completely killed by the heat during a VSV process. However, because bacteria are very small, it is possible for some of them to enter the tiny pores and cracks under the surface. These pores and cracks may actually be filled with water, which prevented them from contacting with steam directly. Also, because of the unique property of steam, it immediately condenses when in contact with a cold surface. Because of the condensation, steam may not freely enter the small pores and cracks under the surface to release its immense latent heat. A possibility also exists that the small pores and cracks may actually be "sealed off" under the intense pres-

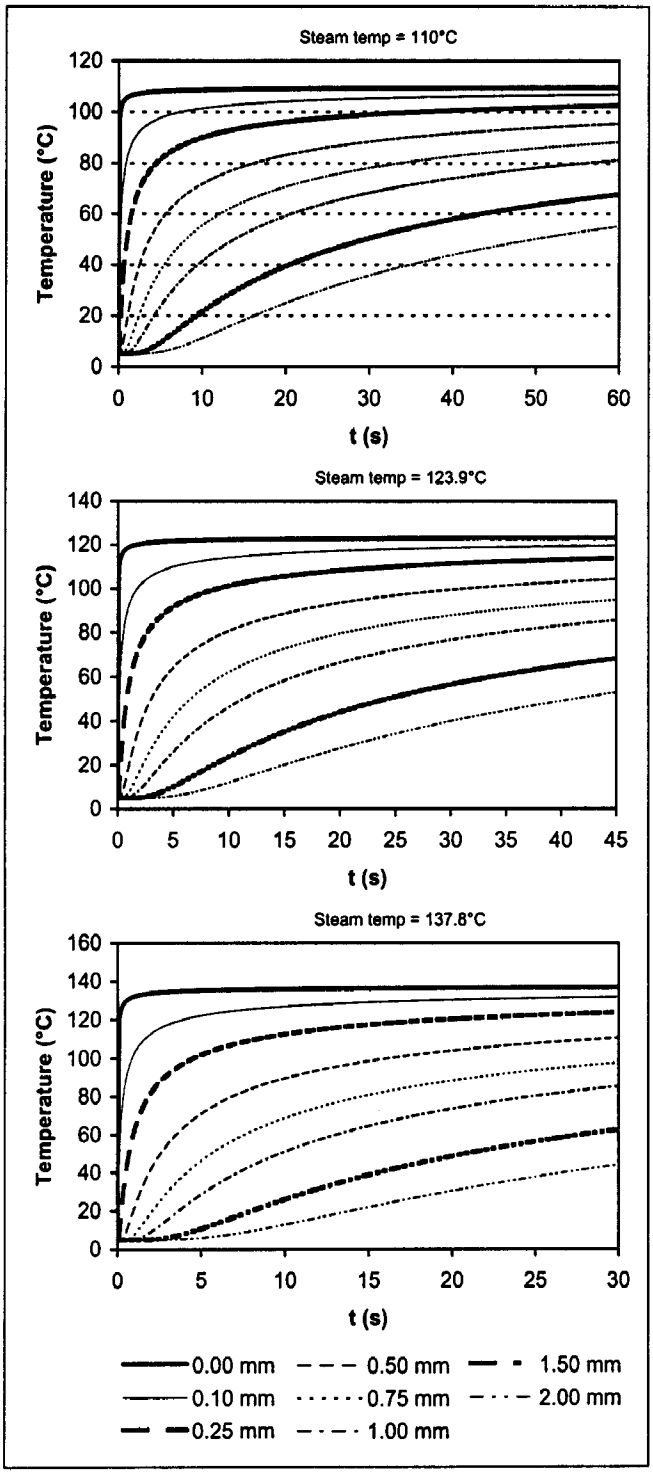

Figure 4—Simulated temperature distribution at different locations below the surface of hot dogs

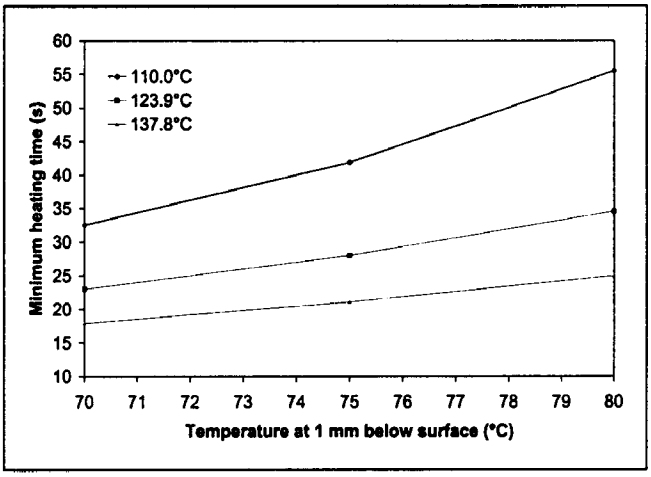

Figure 5—Minimum heating time required for the temperature at 1 mm below hot dogs surface to reach 70 °C, 75 °C, and 80°C under a constant ambient temperature

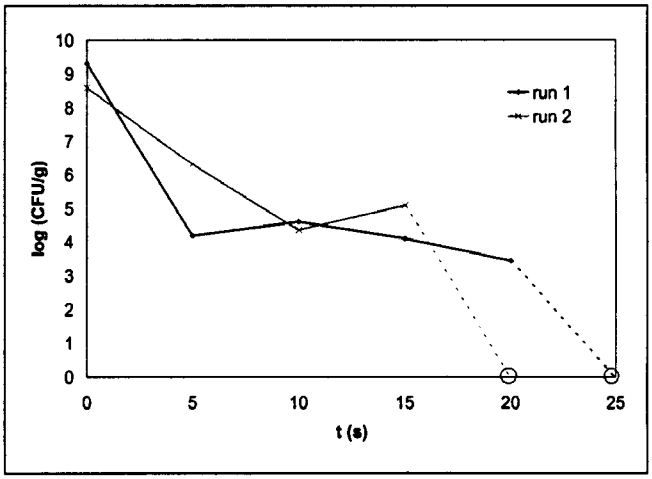

Figure 6—Survival of *Listeria Innocua* (SA3-VT) after steam treatment at 137.8°C. Survivors were recovered by direct plating onto TSA plates. Points represented by empty circles indicate that no viable cells of *L. innocua* were directly recovered from hot dogs after surface pasteurization.

sure differential after the steam fluxed into the treatment chamber, further preventing the contact between the steam and bacteria. Because the heating time in each treatment cycle is extremely short (in the range of milliseconds) and heat is immediately removed by the following vacuum procedure, and also because the thermal diffusivity of hot dogs is very low, in spite of multiple cycles, the heat released by the steam onto the surface of solid foods may not have sufficient time to penetrate into the small pores and cracks. As a result, the bacteria hiding in these areas are likely never touched by the steam, and therefore survive the heating. Depending on the structure and complexity of the pores and cracks, different amounts of bacteria may hide in these areas. For smooth surfaces such as hot dogs and some fruits, the majority of bacteria are distributed on the surface. Only a small amount (1 to 2 logs) is located in the small pores and cracks. As a result, VSV processes can kill the majority of bacteria on the surface, leaving a small amount of bacteria hiding in the pores and cracks intact. For rough surfaces such as chickens, catfish, and ham meat or skin, the majority of bacteria are harbored in the complex structure of the pores and cracks. Therefore, VSV processes can kill only a small amount of the bacteria directly exposed to the steam, whereas the majority of bacteria in the pores and cracks are protected from being inactivated. Consequently, a large amount of bacteria survive the heating.

Initial vacuum and vacuum between cycles

The initial vacuum was originally proposed to remove vapor and air from the pores and irregularities below the surface of solid foods to allow steam to flow freely and directly into these areas (Morgan 1994; Morgan and others 1996a, 1996b). It is not theoretically or practically clear whether the initial vacuum could facilitate the flow of steam to flow freely and directly into the pores below the surface because all the pores are "dead-ended." However, as long as there exists some liquid water in the pores below the surface and there are bacteria in them, heat must penetrate into these areas by conduction, which is a very slow process. The initial vacuum serves no benefit if conduction is the rate-limiting factor during heat transfer. Therefore, the initial vacuum might not be necessary.

To inactivate the bacteria hiding the pores below the surface, it is necessary to maintain the temperature of the steam for an extended period of time. Using multiple cycles of steam treatment interrupts the process of heat transfer, thereby allowing the bacteria hiding in the pores below the surface to survive the heat treatment. The intermittent vacuum also hinders the transfer of heat into the pores. The intermittent vacuum not only removes the steam from the chamber but also induces a layer of condensate on the hot dog surface. This explains why all the food samples are "wetter" after the VSV treatment. The condensate may seal the entrance to the pores and add an additional layer of heat resistance for the subsequent steam cycle.

That vacuum may not be needed in the steam surface pasteurization of foods is also supported by the data available in the literature. Studies by Kozempel and others (2000a, 2000b, 2001b, 2002) consistently indicated that steam temperature was a statistically significant factor for the reduction in the bacterial counts after VSV treatment, although the decrease in bacterial counts was not proportional to the increase in temperature. The initial vacuum time and between-cycles and final vacuum times had no effect on reducing the bacterial counts (Kozempel and others 2000a, 2000b). The same studies also showed that the effect of steam time was not significant, which suggests that bacteria located below the surface were not directly exposed to the lethal power of the high-temperature saturated steam. Therefore, a consistent amount of bacteria always survived the VSV treatments.

These studies, however, reported that the number of cycles was a significant factor in reducing the bacterial counts after VSV treatment. This observation is also explainable. Kozempel and others (2000b) observed that the counts of *L. innocua* remained the same in hot dogs after the 1st cycle for multiple cycles (0.1 s/cycle) or 0.1 s in a single cycle of steam treatment (Figure 7). This can be explained by the fact that a significant number of bacteria superficially attached to the skin layer of hot dogs were killed during the first 0.1 s in a single cycle treatment or in the 1st cycle (also 0.1 s). After the first 0.1 s or the 1st cycle, heating time was not sufficient to inactivate the bacteria hiding in the pores below the surface. Therefore, the bacterial counts remained the same. However, when the bacterial counts recovered from hot dogs after multiple cycles of treatment were compared with the original counts, the effect of cycle numbers became statistically significant. In reality, the extent of bacterial removal after 0.1 s was similar for single or multiple-cycle treatments, which indicates that it may not be necessary to use multiple cycle treatments. If the bacteria counts after 0.1 s were used in statistical analysis, the effect of multiple cycles would not be significant.

Conclusions

This study confirmed the hypothesis that steam could not enter the small pores, cavities, and other irregularities under the surface of hot dogs. Therefore *L. monocytogenes* hiding in these locations would be prevented from being directly exposed to the lethal effects of high-temperature steam and thus could not be inactivated by short cycles of VSV treatment used in previous research. To kill all pathogens, such as *L. monocytogenes*, heat must be applied so that a thin layer immediately below the surface of hot dogs could reach a minimum temperature lethal to the organisms. This is a much slower heat-conduction process, which would not be affected by the structure, size, and distribution of the pores, cavities, and other irregularities underneath the surface of hot dogs. Only the depth and steam temperature would determine the minimum heating time required to render hot dogs free from *L. monocytogenes*. In this study, it was hypothesized that the deepest pores, cavities, and other irregularities were about 1 mm below the surface of hot dogs. According to computer simulation, the minimum time needed for the layer 1 mm below the hot dog surface to reach 80 °C

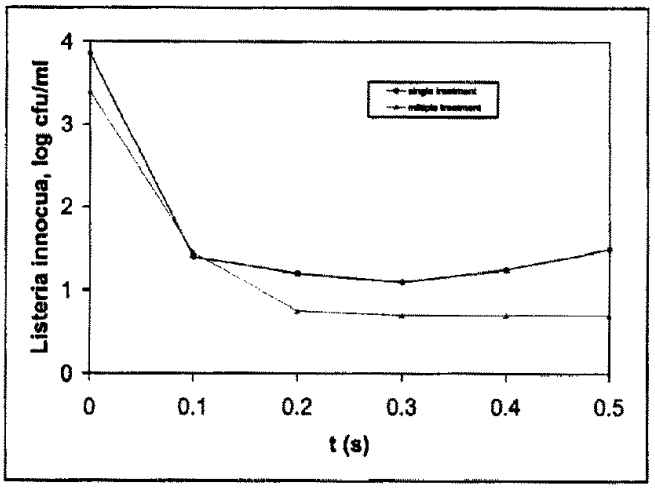

Figure 7—Effect of cycles during vacuum-steam-vacuum (VSV). This figure is reproduced from Figure 3 (Kozempel and others 2000b). Each cycle is a complete sequence of vacuum, steam, and vacuum in a VSV process.

was 55.5, 34.6, and 25 s, respectively under 110 °C, 123.9 °C, and 137.8° of saturated steam. The computer simulation results were confirmed by microbiological validation tests conducted using 137.8 °C (280 °F) steam. After 25 s of uninterrupted steam treatment, no *L. innocua* inoculated onto hot dogs were detected, indicating a complete destruction of this organism. The results of this study provided a new understanding of the mechanism of bacterial inactivation during steam surface pasteurization of hot dogs or other cooked meats and can be used to design effective processes to produce *L. monocytogenes*–free products in the food industry.

Acknowledgments

Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Dept. of Agriculture.

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